

Inclusive Jets and Dijet Production at the Tevatron

Recent jet results from the DØ
and CDF Collaborations

- Inclusive Jet Cross Section
- Dijet Angular Distributions

Bob Hirosky
S.C.R.I.
for the
DØ and CDF Collaborations

Inclusive Jet Cross Section

$$\frac{1}{\Delta\eta} \int d\eta \frac{d^2\sigma}{dE_T d\eta} = \frac{1}{\Delta\eta} \frac{1}{L} \frac{N_{jet}}{\Delta E_T}$$

Precision measurement of inclusive jet cross section =>

- Strong Test of PQCD and PDF models

NLO Calculations: Aversa et al. Nu. Phy. B327 (1989)
Ellis et al. PRL 64 (1990)
Giele et al. Nu. Phy. B403 (1993)

- Search for new physics:

Large statistics of DØ and CDF data provide unique probe for distance scales to $\sim 10^{-17}$ cm

Inclusive Jet Production Data Sets

Collider Run	DØ Luminosity	CDF Luminosity
1992-1993	13 pb^{-1}	19 pb^{-1}
1994-1995	93 pb^{-1}	87 pb^{-1}

Event & Jet Selection

- Eliminate events w/ large Missing E_T
- Apply Jet Quality Cuts
- $|Z_{\text{vertex}}| < 50 \text{ cm}$ (DØ); $< 60 \text{ cm}$ (CDF)
- $|\eta| < 0.5$ (DØ) ; $0.1 < |\eta| < 0.7$ (CDF)
- $R = 0.7$ Jet Cone Algorithm

Corrections to Jet Cross Section

- D_Ø Energy Scale (Re-evaluated in '96-97)

Corrections determined from data --- applied on a jet by jet basis:

$$E_{\text{jet}} = (E_{\text{measured}} - O) / [R_{\text{had}} (1 - S)]$$

O = offset due to noise, pileup, underlying evt.

R_{had} = hadronic response correction.

Determined from Missing E_T balance in photon-jet events. (EM calibration established via Z, J/Ψ and π^0 resonances)

S = showering losses. Negligible for 0.7 cone

- CDF Energy Scale

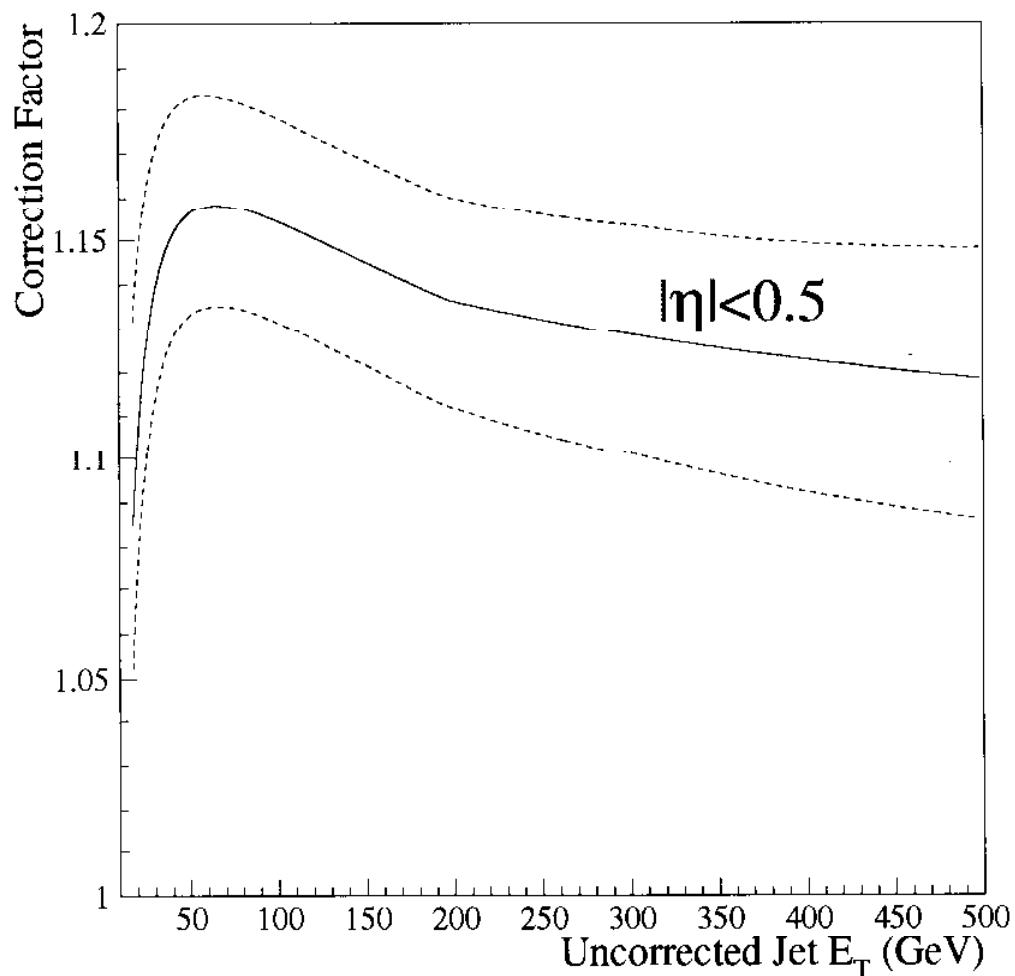
Detector response correction determined from MC simulations and applied on statistical basis to measured jet cross section

Energy correction for underlying evt. included

No showering loss correction applied

DØ Average Jet Scale Correction Factor vs. Uncorrected E_T

(New analysis -> improved systematics)



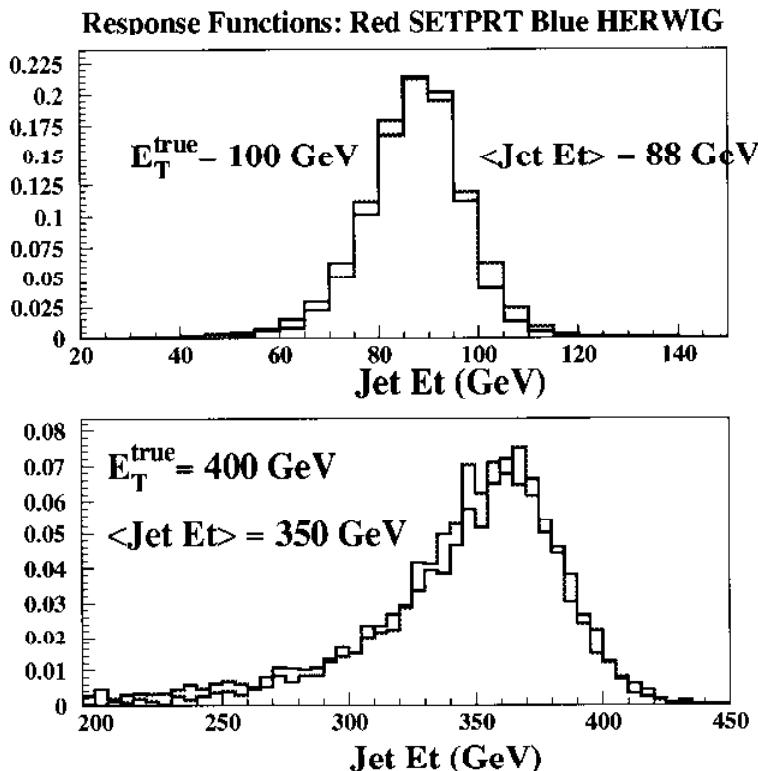
	E_T (GeV)	New analysis	1996
Average Correction Factor	70	$16.0 \pm 2.0\%$	$18.5 \pm 3\%$
	400	$12.5 \pm 2.6\%$	$13.5 \pm 5\%$

CDF

Corrections to Jet Cross Section Response Functions

For a given True E_T the Response Function is the distribution in measured E_T .

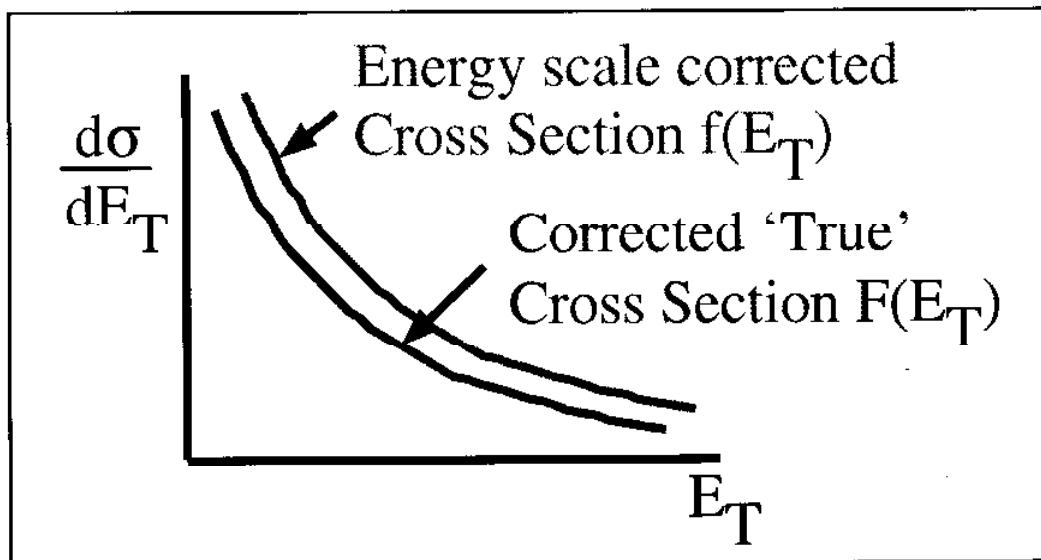
True $E_T \equiv$ Sum over particles in the Jet Cone



Jet Resolution = width of response function
 $\sigma_{RMS} \approx 0.1E_T + 1$ GeV for $35 \leq E_T \leq 450$ GeV

Jet Resolution & Unsmearing

Finite E_T resolutions flatten Cross Section



DØ

Jet resolutions (σ_{ET} / E_T) measured in data via dijet asymmetry:

$$A = (E_{T1} - E_{T2}) / (E_{T1} + E_{T2})$$

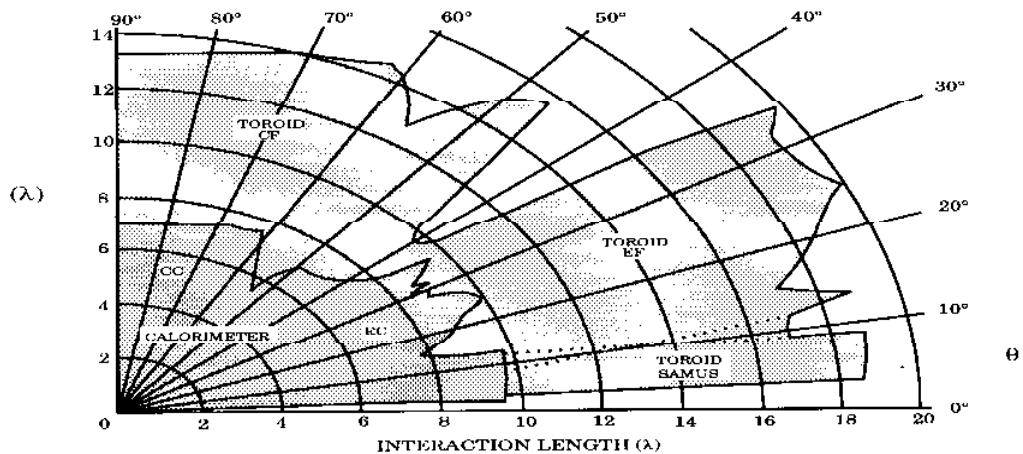
In the limit of no soft radiation, both jets of nearly equal E_T and rapidity:

$$\sigma_A = \sigma_{ET} / (\sqrt{2} E_T)$$

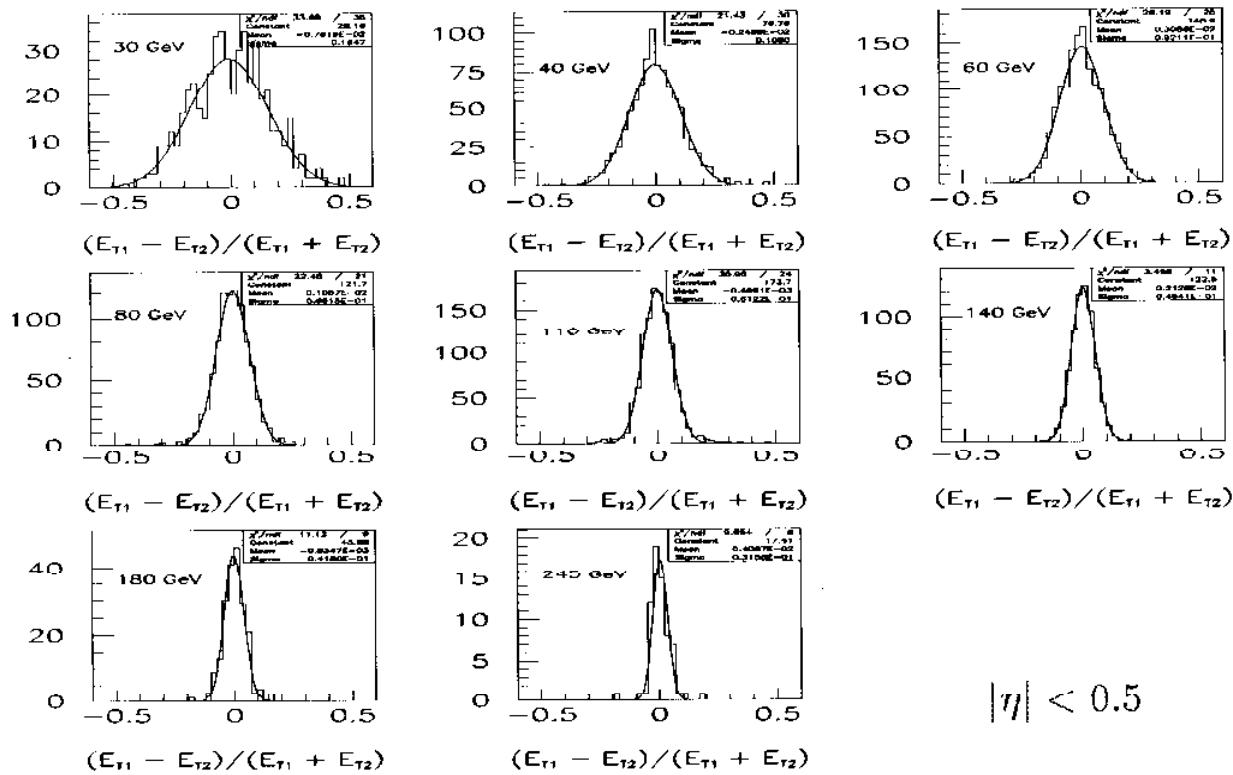
(Corrections included for soft radiation and particles radiated outside jet cones)

DØ

Calorimeter Depth



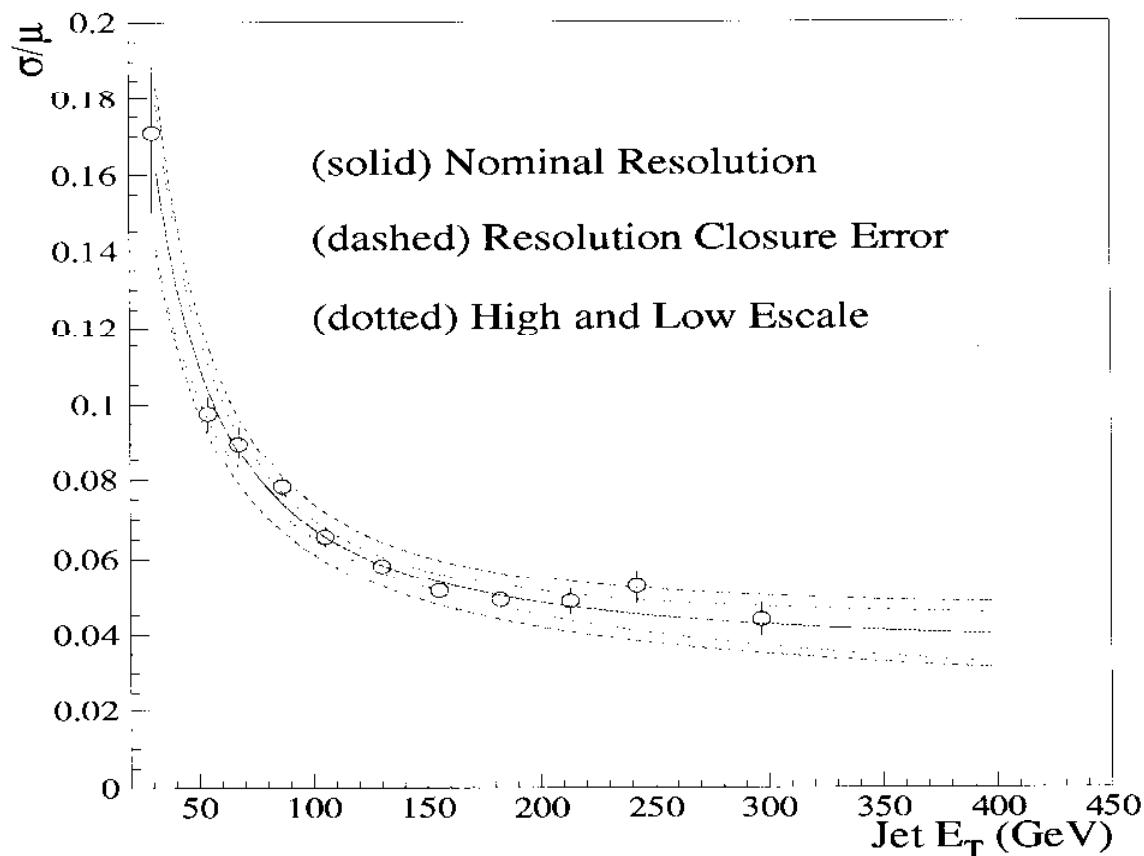
Asymmetry Distributions



R.Hirosky DIS97 Chicago

DØ

Fractional Jet E_T Resolution (σ_{ET}/E_T) vs. Corrected Jet E_T



Jet E_T (GeV)	Jet E_T Resolution
50	11%
100	6.5%
400	4%

UNSMEARING

DØ

The observed E_T spectrum is corrected for resolution with an unsmeared procedure.

An assumed "physics curve," $F(E_T, P_i)$, is convoluted with measured resolutions and compared to the measured cross section.

Parameters, P_i , are adjusted to match the data:

$$\begin{aligned} f(E_T) &= F(E_T, P_i) \otimes R(E_T) \\ \text{observed} & \quad = \quad \text{true} \quad \otimes \quad \text{resolution} \\ \text{cross section} & \quad \quad \quad \text{cross section} \quad \quad \quad \text{function} \end{aligned}$$

and $F(E_T, P_i) = A (E_T)^{-B} (1 - 2E_T/\sqrt{s})^C$

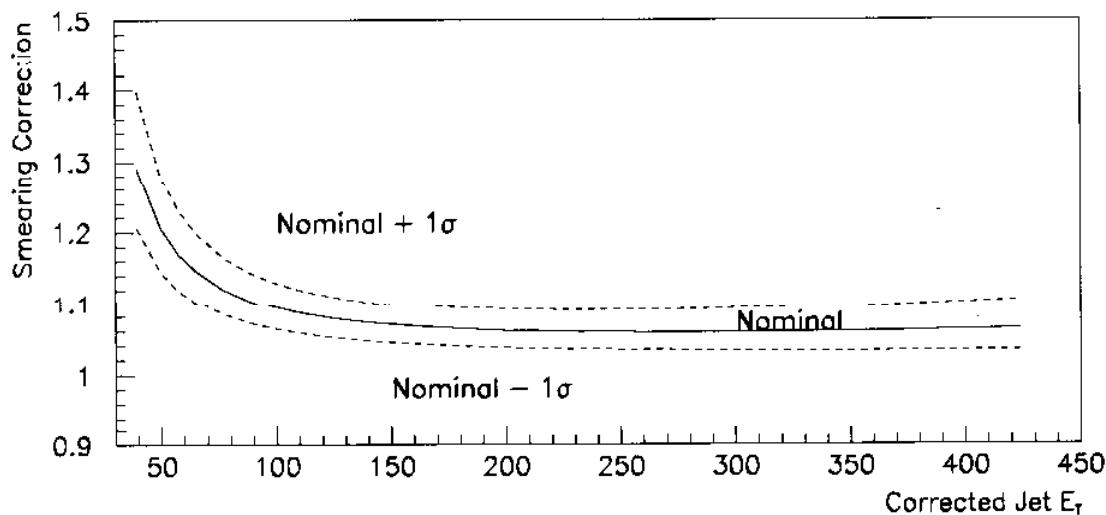
CDF

Similar unsmeared technique, but resolution function is generalized to include jet response as well.

DØ

Unsmearing Correction for Cross Section

(Reduces Cross Section by Smearing Factor)



E_T (GeV)	Unsmearing Correction
40	$\sim 1.29 \pm 0.10$
60	$\sim 1.16 \pm 0.07$
200	$\sim 1.06 \pm 0.03$
420	$\sim 1.08 \pm 0.04$

CDF

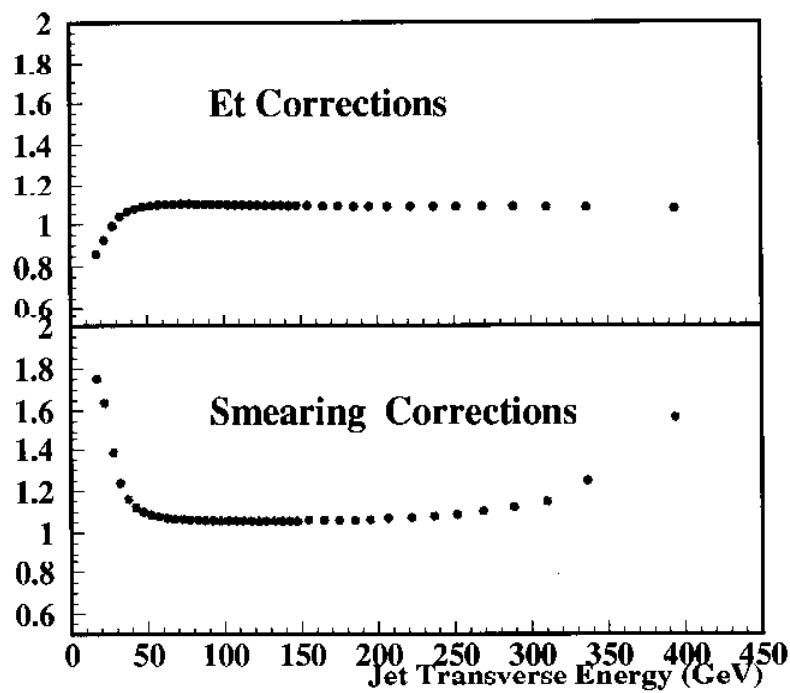
Cross Section Corrections:
for each bin of measured E_T

- Horizontal: from response functions

$$E_T \text{ correction} \equiv \frac{\langle E_T^{\text{true}} \rangle}{\langle E_T^{\text{smeared}} \rangle}$$

- Vertical shift for each bin

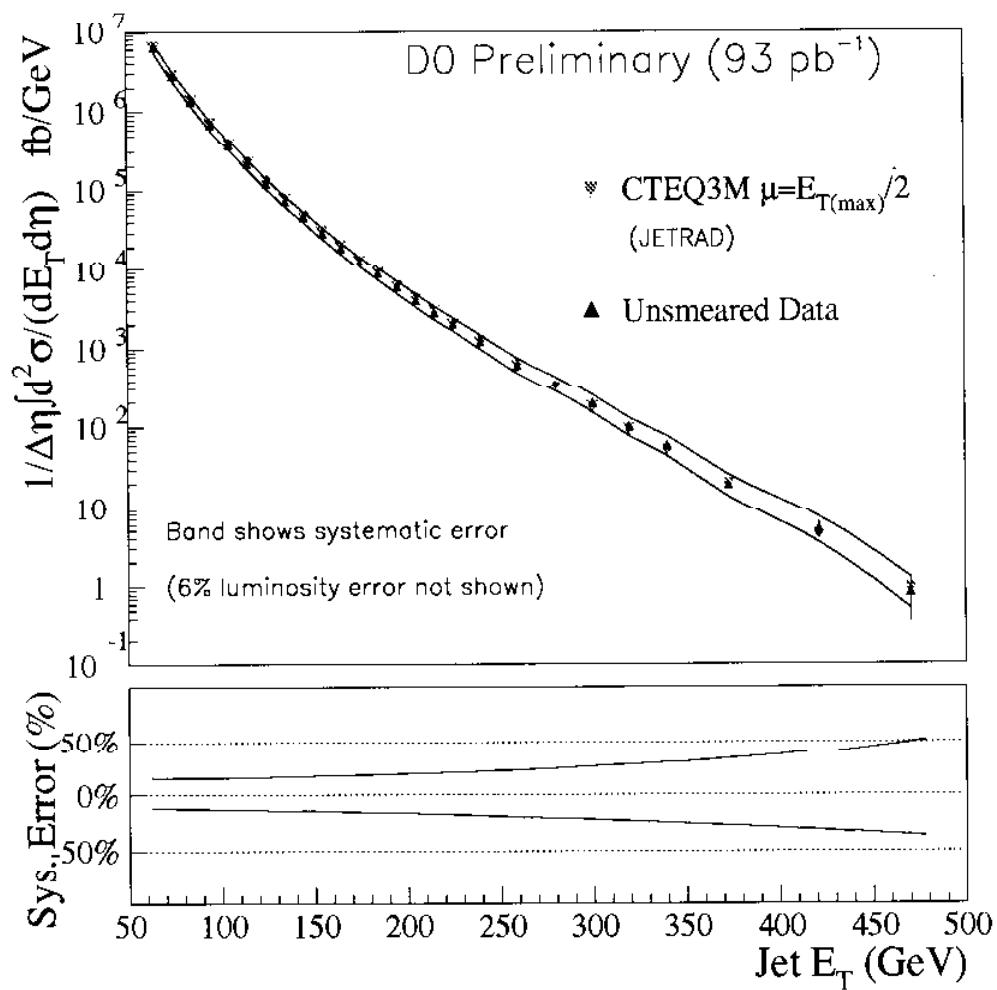
$$\text{smearing correction} \equiv \frac{\sigma^{\text{true}}(\langle E_T^{\text{true}} \rangle)}{\sigma^{\text{smeared}}(\text{Bin})}$$



DØ

Inclusive Jet Cross Section

$|\eta_{\text{jet}}| < 0.5$



Theory

Programs for NLO Calculation:

JETRAD (Giele, Glover, Kosower)
EKS (Ellis, Kunszt, Soper)

Choices in calculation:

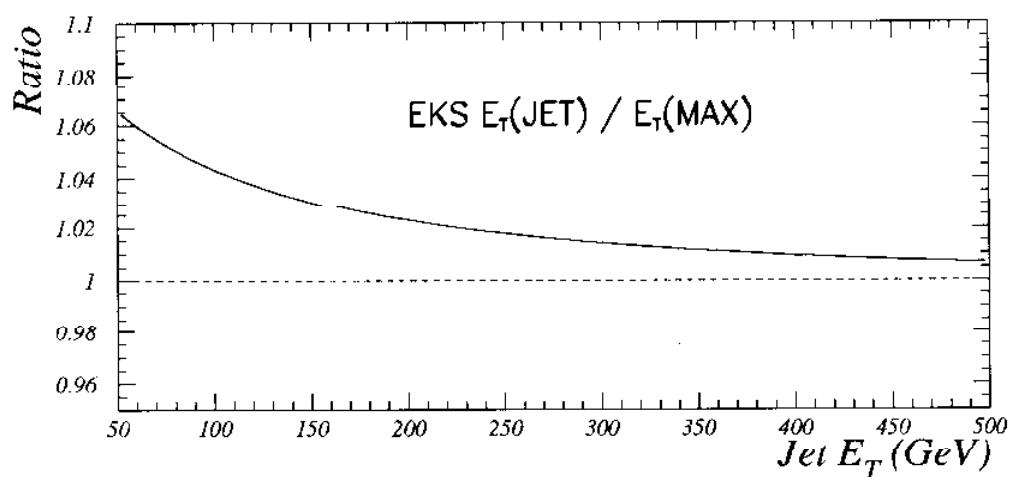
PDF's

Clustering Algorithm

Renormalization/Factorization Scale

~10% normalization range for
scales $\sim E_T$ * (0.25 \rightarrow 2.0)

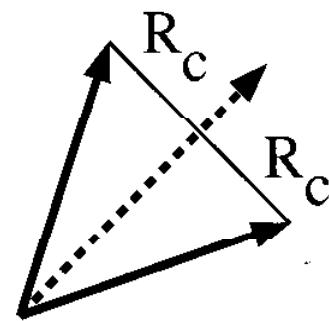
Shape changes w/ definition



Clustering of Partons at NLO

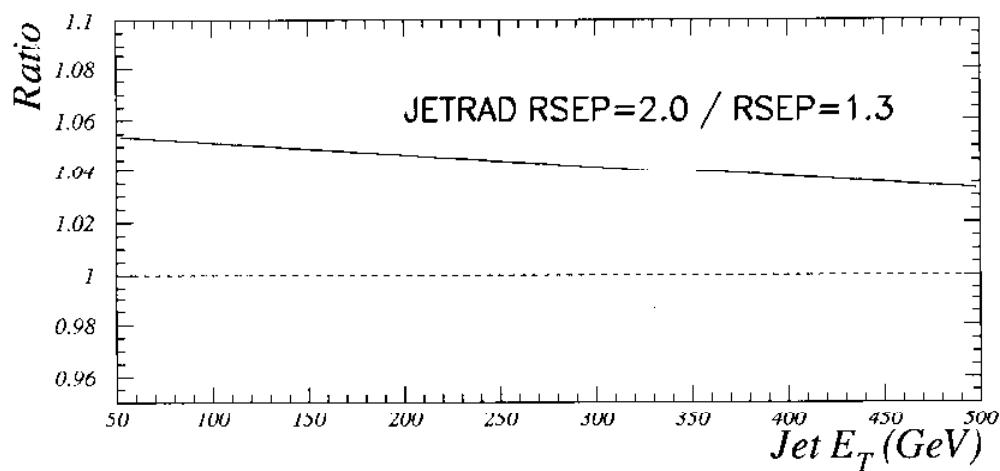
1) Each parton must be w/in $R_c = 0.7$ of jet centroid (Standard Snowmass definition)

Used by CDF



2) The two partons must be within $R_{sep} * R_c$ of one another, where R_{sep} varies from 1-2.

DØ uses $R_{sep}=1.3$ to match jet split/merge conditions in data and MC



Typical Theory Choices for each Experiment

DØ:

Program: JETRAD

Clustering: Snowmass, Rsep=1.3

$\mu_R, \mu_F: E_{T\max} / 2$

CDF:

Program: EKS

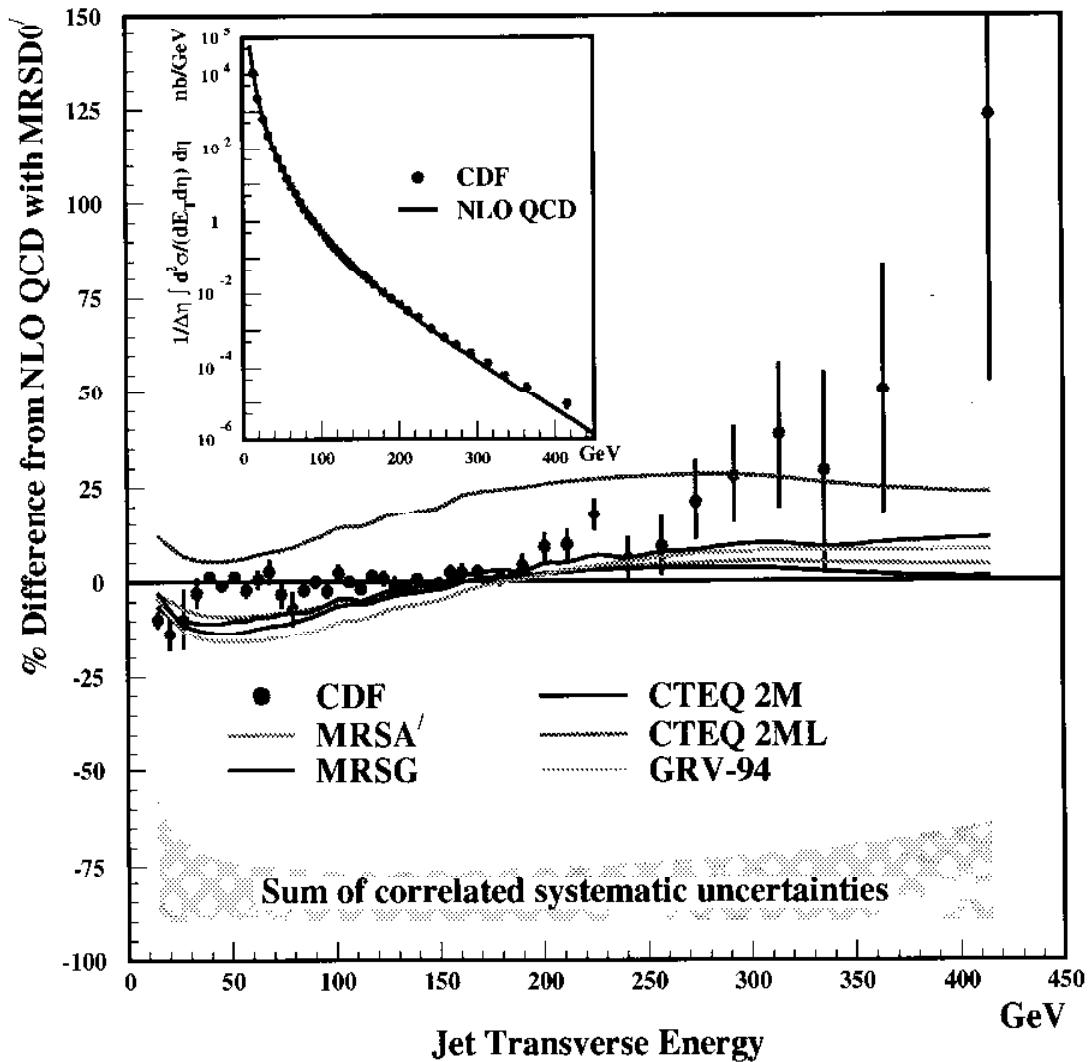
Clustering: Snowmass, Rsep=2.0

$\mu_R, \mu_F: E_{T\text{jet}} / 2$

CDF Inclusive Jet Cross Section (1992-93)

PRL 77, 438 (1996)

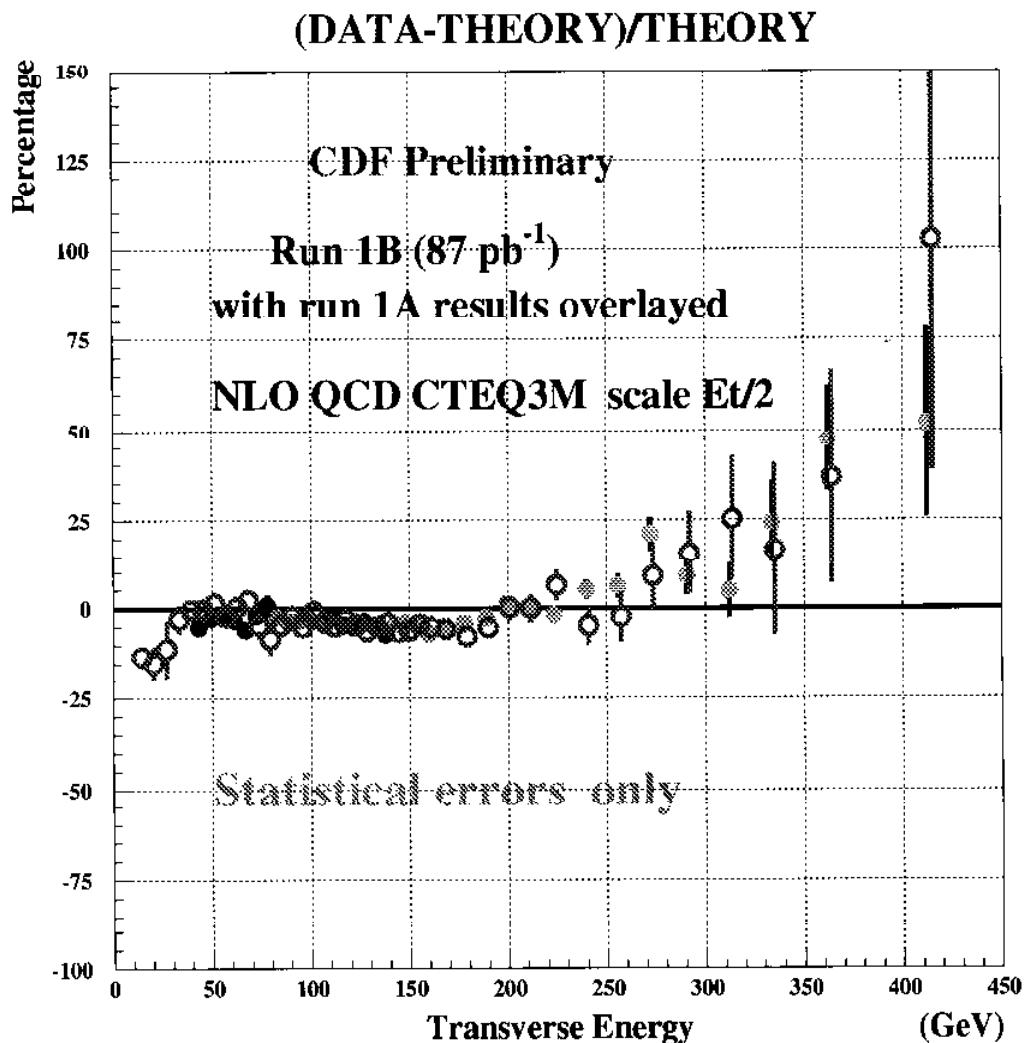
$0.1 < |\eta| < 0.7$



- Good agreement w/ QCD < 200 GeV
- Significant excess > 200 GeV, not fully accounted for by systematic errors

CDF Inclusive Jet Cross Section (1994-95)

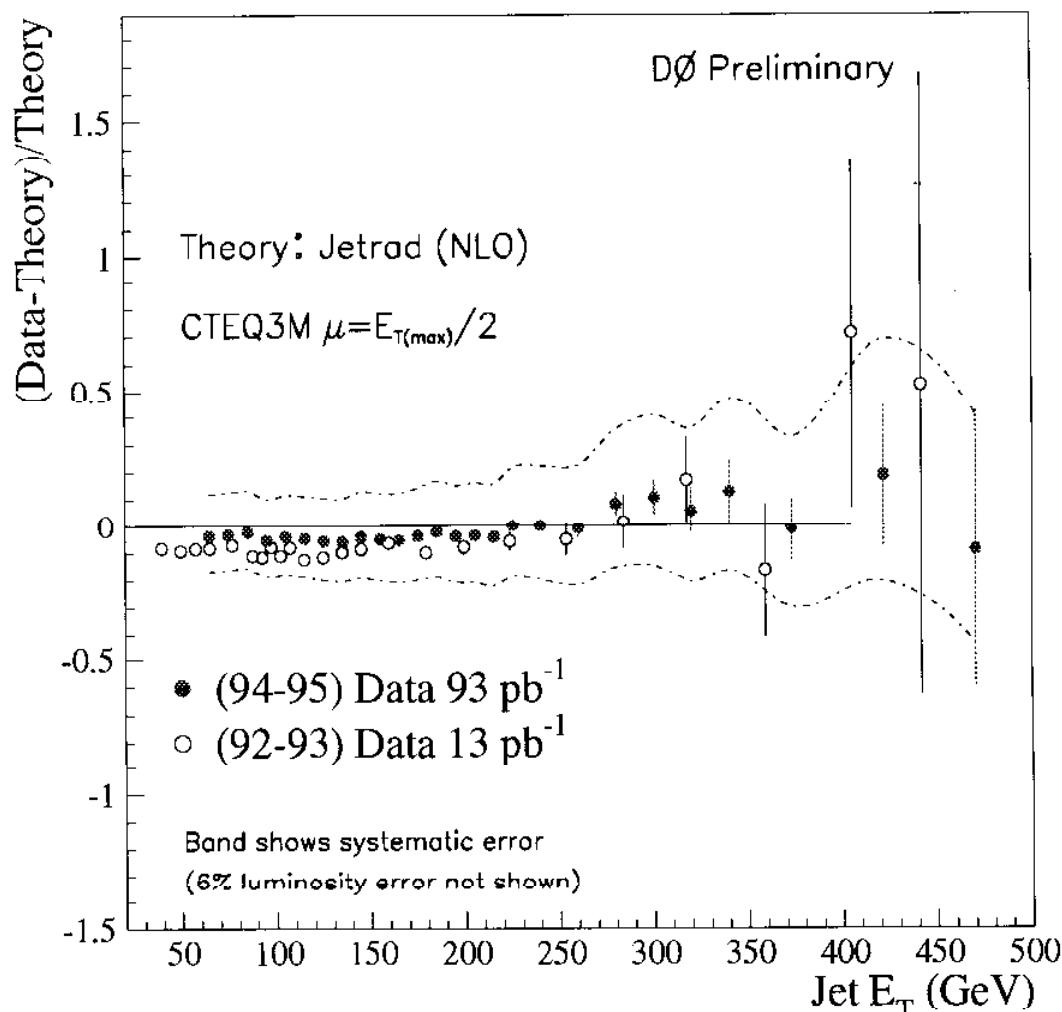
$$0.1 < |\eta| < 0.7$$



Luminosity Uncertainty $\sim 10\%$

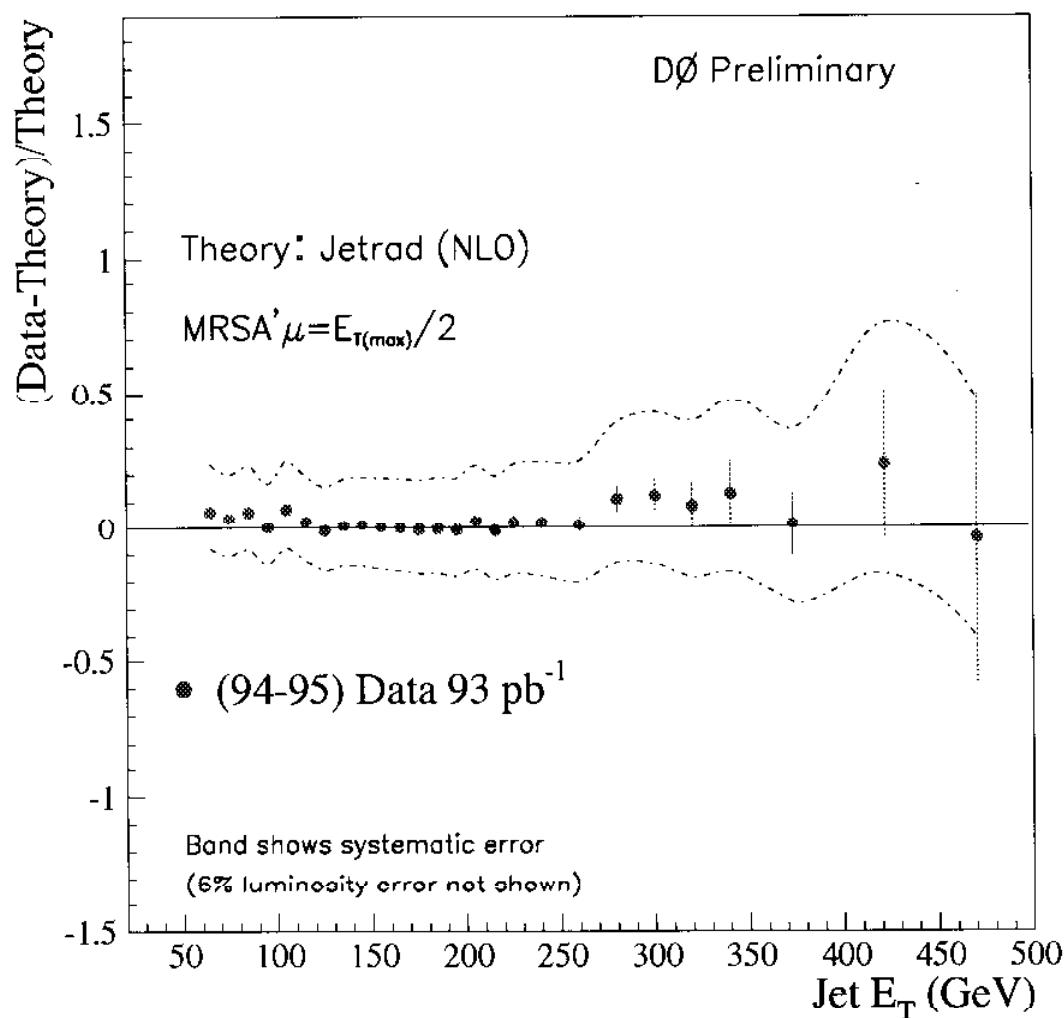
Systematic errors not finalized, but expected to be similar to published results

DØ Inclusive Jet Cross Section (1994-95) $|\eta| < 0.5$



- Good agreement w/ QCD

DØ Inclusive Jet Cross Section (1994-95) $|\eta| < 0.5$

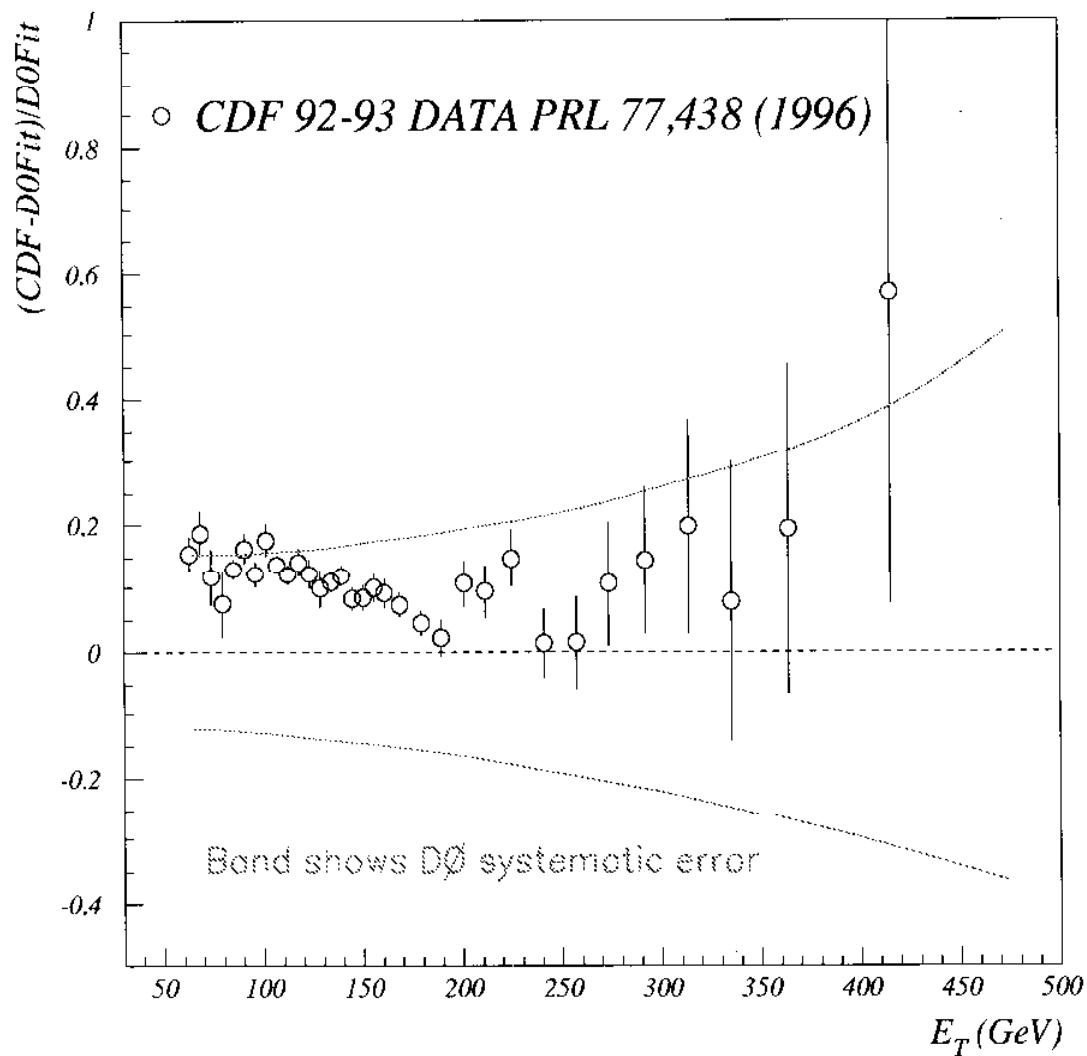


Comparison of Experimental Cross Sections

Repeat D \emptyset analysis with CDF fiducial cuts

$$0.1 < |\eta_{\text{jet}}| < 0.7$$

Compare CDF 1A (1992-3) data w/ fit to D \emptyset
Cross Section Preliminary

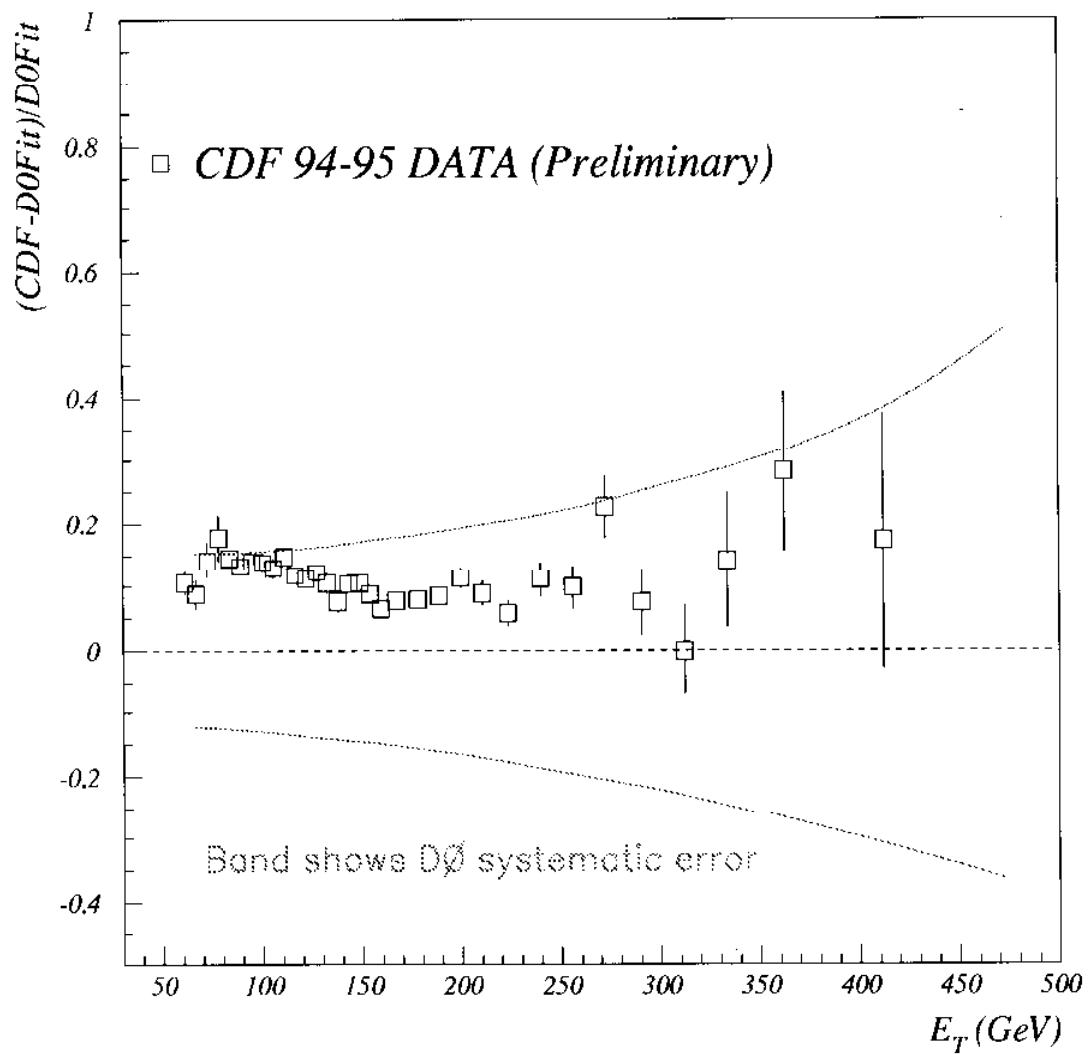


Comparison of Experimental Cross Sections

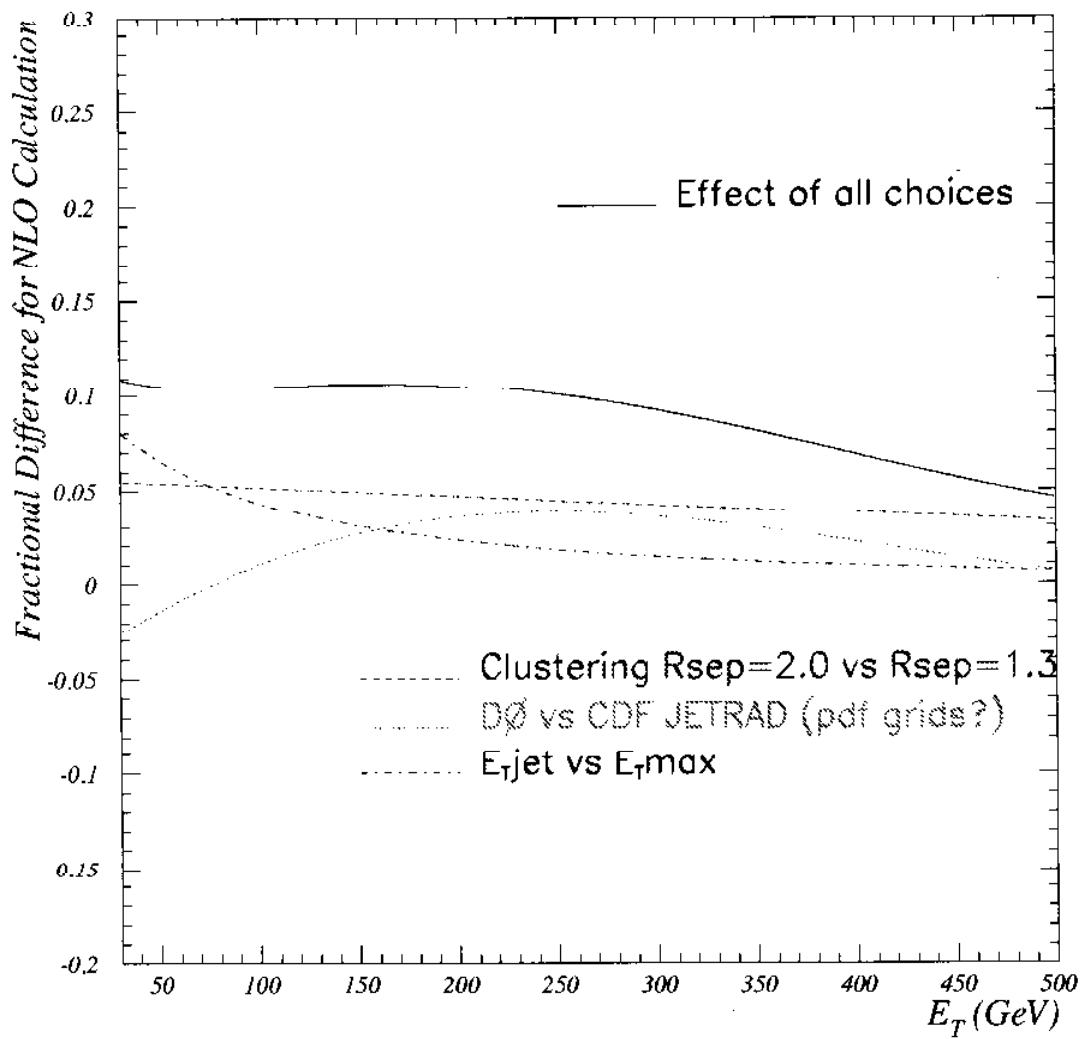
Repeat D \emptyset analysis with CDF fiducial cuts

$$0.1 < |\eta_{\text{jet}}| < 0.7$$

Compare CDF 1B (1994-5) data w/ fit to D \emptyset
Cross Section Preliminary



- Both experiments agree with respective theory choices in intermediate or full E_T range
- How do these choices add up?



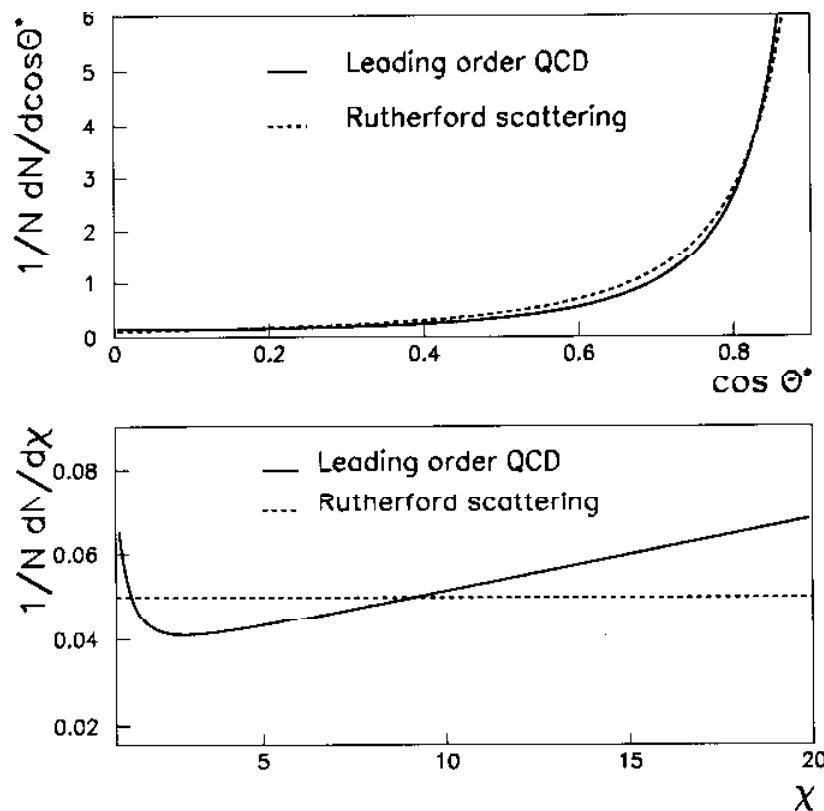
Effect of all choices

Dijet Angular Distribution

Measure: $\frac{1}{N} \frac{dN}{d\chi}$ vs. χ for different mass bins

$$\chi = e^{(\eta_1 - \eta_2)} = \frac{1 + \cos\theta^*}{1 - \cos\theta^*}$$

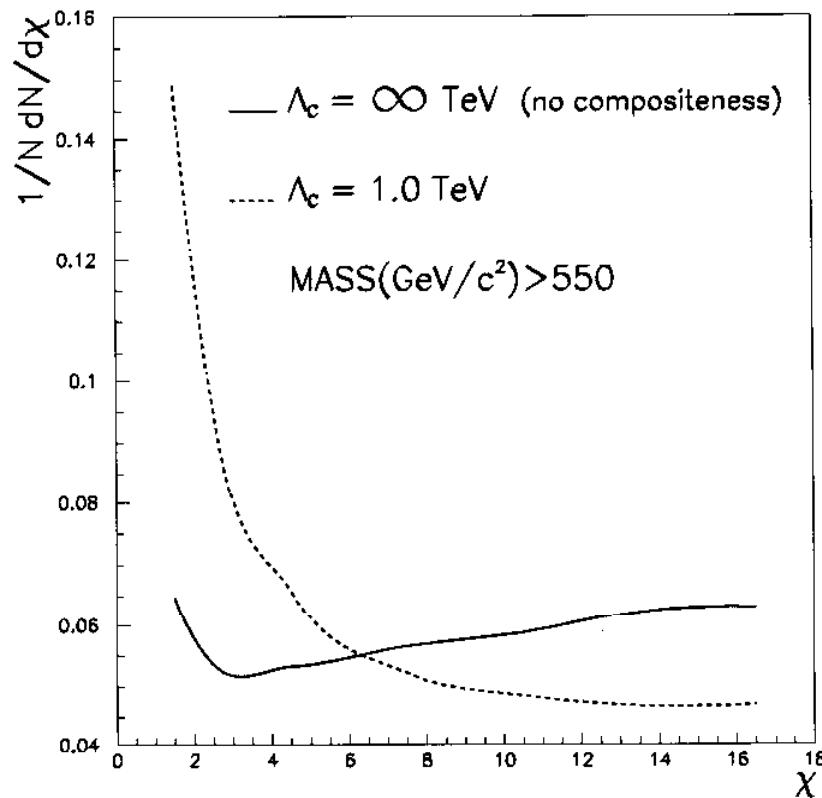
χ flattens out the angular distribution and facilitates comparison with theory



Dijet Angular Distribution

Direct test of PQCD

- $1/N dN/d\chi$ is insensitive to pdfs
gg->gg, gq->gq, qq->qq produce similar angular distributions
- Insensitive to overall energy scale, but affected by η -dependent response variations
 $dN/d\chi$ IS sensitive to contact interactions introduced by compositeness



Event Samples and Selection

- 1994–95 data 94 pb^{-1} **DØ**
- $|\eta_1|, |\eta_2| < 3.0, |\eta_{\text{boost}}| < 1.5$
- choose χ_{max} to ensure full trigger efficiency

DØ Preliminary

Mass Range	<Mass>	χ_{max}	#events
260-425	302	20	4621
425-475	447	20	1573
475-635	524	13	8789
>635	700	11	1074

- 1992-3, 1994-5 data, 106 pb^{-1}
- $|\eta_1|, |\eta_2| < 2.0, \chi_{\text{max}} < 5.0$

CDF

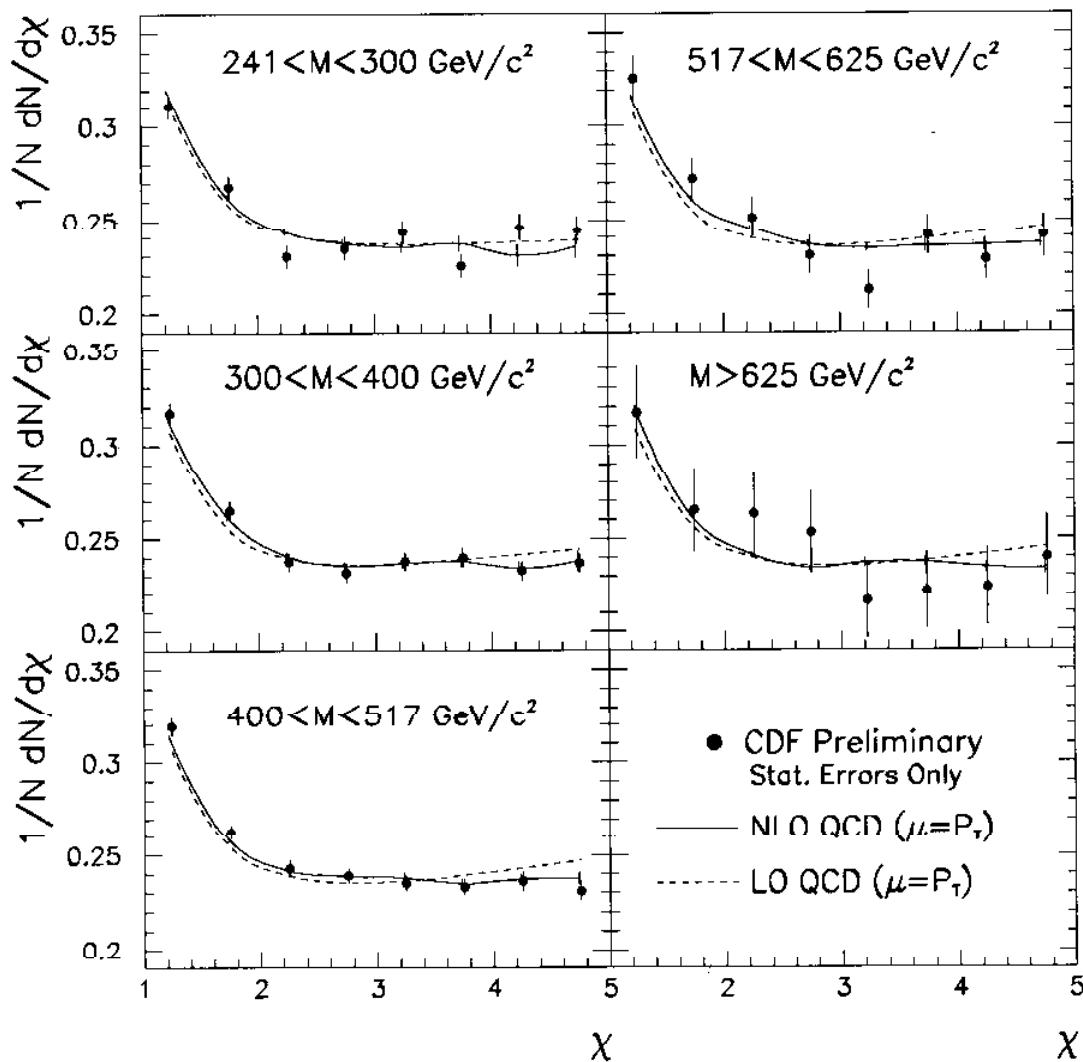
Mass Range	<Mass>	χ_{max}	#events
241-300	263	5	15023
300-400	334	5	23227
400-517	440	5	28202
517-625	557	5	4425
>625	698	5	1056

CDF Dijet Angular Distribution

Comparison w/ theory:

JETRAD NLO and LO, $\mu = E_T(\text{MAX})$

CDF Dijet Angular Distribution and QCD

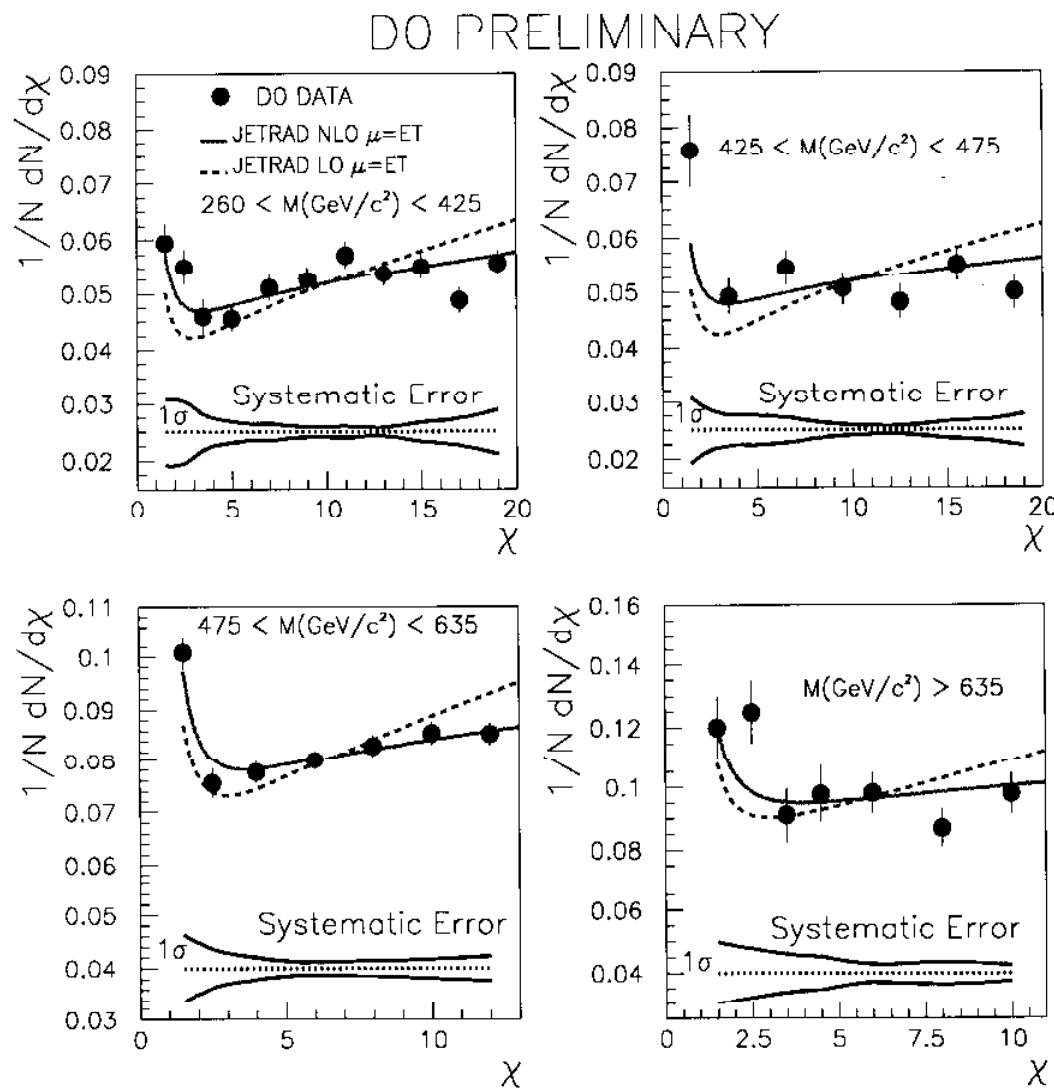


DØ Dijet Angular Distribution

Comparison w/ theory:

JETRAD NLO and LO, CTEQ3M,

$$\mu = E_T(\text{MAX})$$

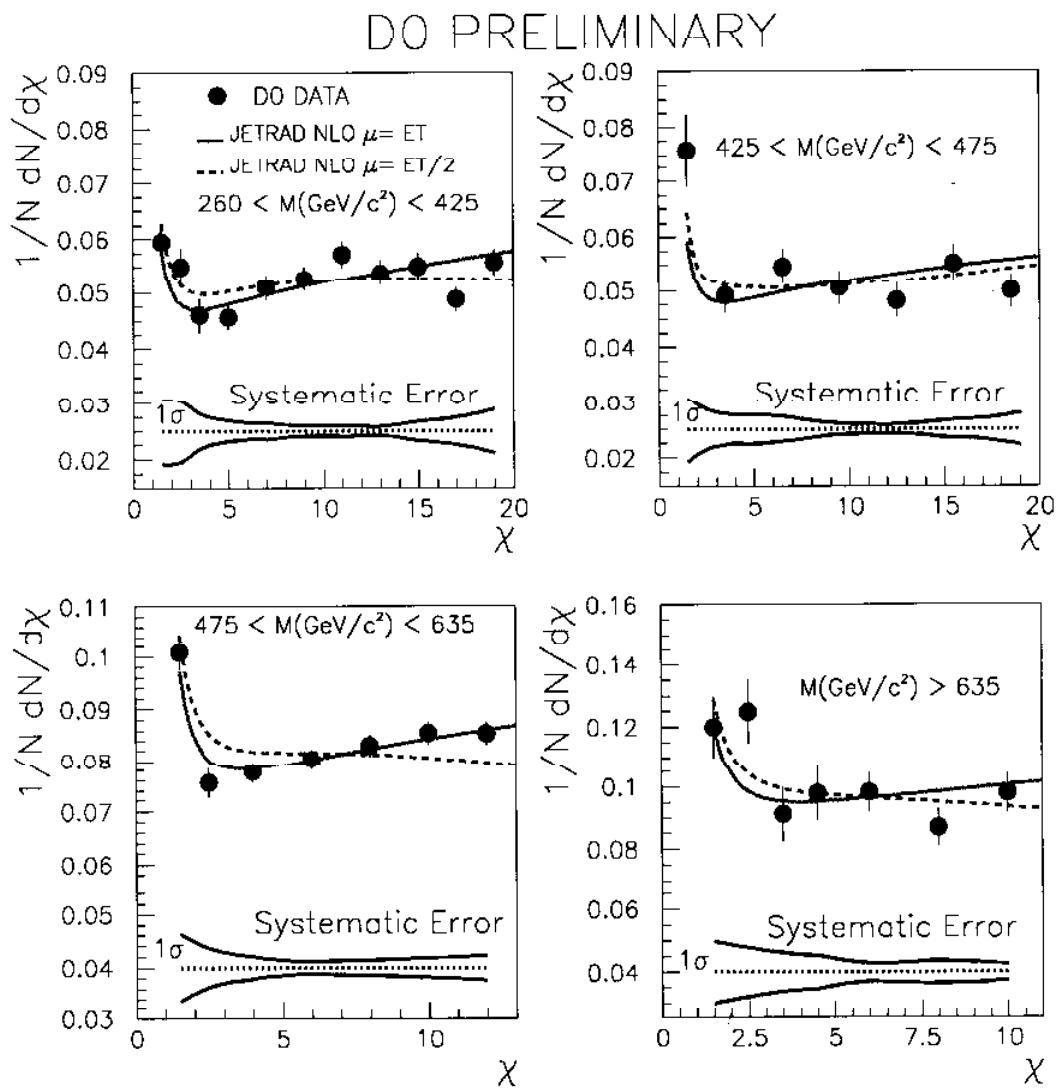


Large χ range \rightarrow good discrimination

DØ Dijet Angular Distribution

Comparison w/ theory:

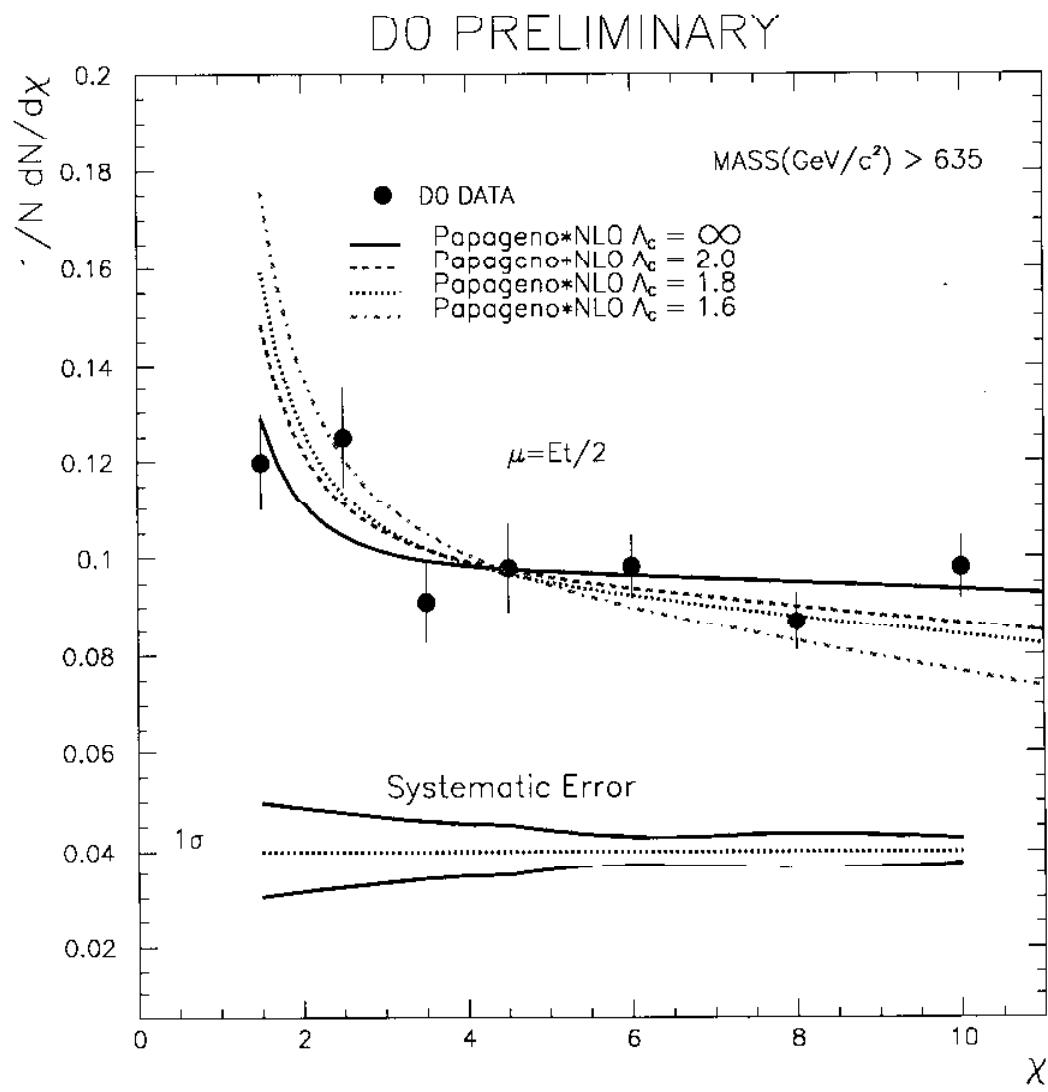
JETRAD NLO, CTEQ3M,
 $\mu = E_T(\text{MAX}) \text{ or } E_T(\text{MAX})/2$



Comparison sensitive to scale choice

DØ Dijet Angular Distribution

Various Scales of Compositeness

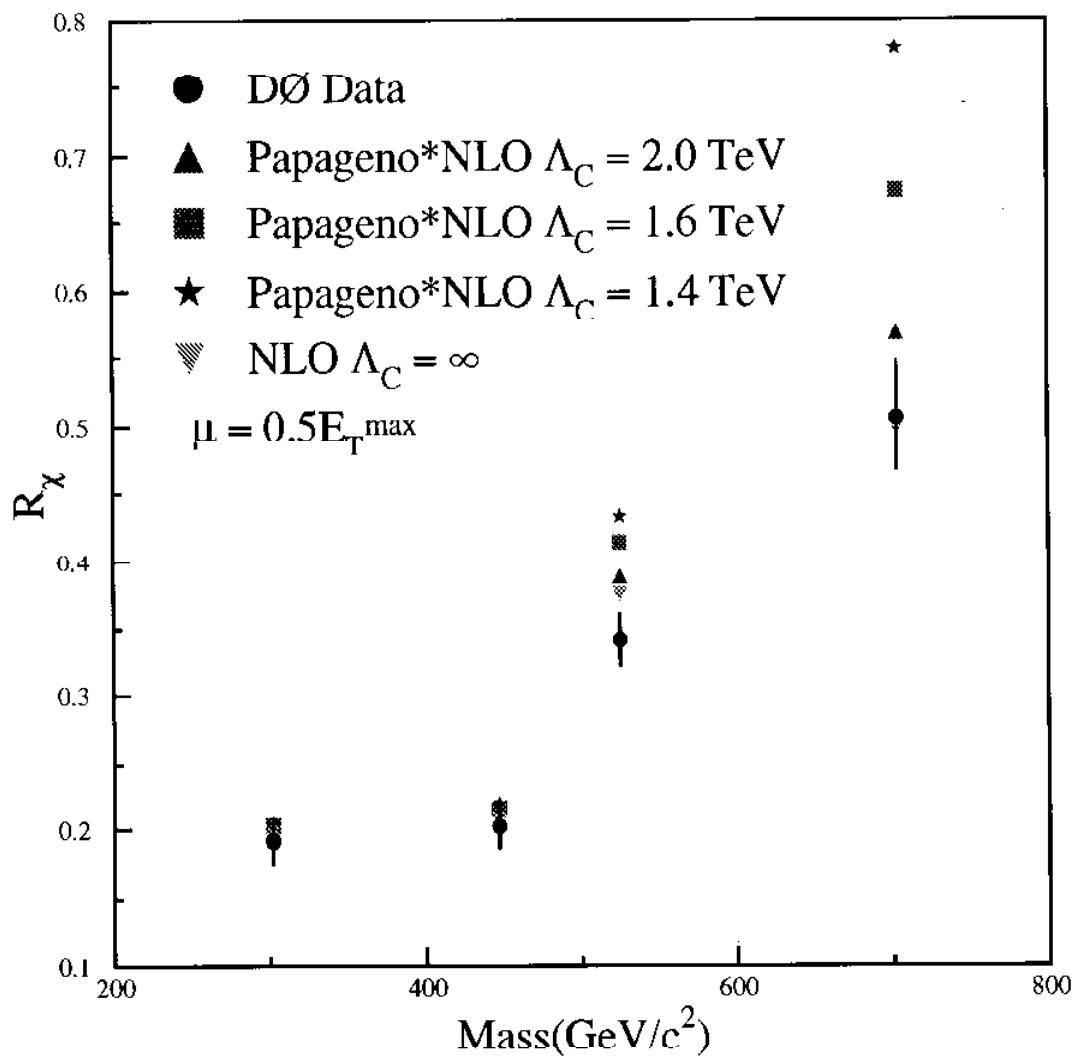


Use NLO JETRAD w/ compositeness correction derived from LO calculation

Limits on Quark Compositeness

CDF	Define R_χ	DØ
# Events ($\chi < 2.5$)		# Events ($\chi < 4.0$)
# Events ($\chi > 2.5$)		# Events ($\chi > 4.0$)

DØ Preliminary



Limits on Quark Compositeness

DØ

Bayesian 95% CL limit for Λ^+ , each renorm.
scale treated as different theory

DØ Preliminary

μ	prior	limit (TeV)
$E_T(\text{max})/2$	$1/\Lambda^2$	2.2
$E_T(\text{max})$	$1/\Lambda^2$	2.0
$E_T(\text{max})/2$	$1/\Lambda^4$	2.0
$E_T(\text{max})$	$1/\Lambda^4$	1.9

CDF

χ^2 95% CL limit for various compositeness
models added to
CTEQ2M, $\mu=E_T(\text{max})$ NLO prediction

model	limit (TeV)
Λ_{ud}^+	1.6
Λ_{ud}^-	1.4
Λ^+	1.8
Λ^-	1.6

Conclusions

- **Inclusive Jet Cross Section:**

DØ Preliminary result shows excellent agreement w/ NLO QCD and modern pdf's for $35 \text{ GeV} < E_T < 450 \text{ GeV}$

Improved systematic errors in new analysis

CDF published data and new analysis in good agreement w/ NLO QCD below 200 GeV, but show an excess $> 200 \text{ GeV}$

Both experiments ~consistent w/in systematic errors

- **Dijet Angular Distribution:**

DØ Preliminary result excludes regions with $\Lambda^+ \leq 2.0 \text{ TeV}$ at 95% CL for model w/ all quarks composite

CDF result excludes regions with $\Lambda^+ \leq 1.8 \text{ TeV}$ and $\Lambda^- \leq 1.6 \text{ TeV}$ at 95% for the same model

Limits also set for models w/ only 1st generation quarks composite

- **Precise data yields powerful constraints on QCD, pdf models, and new physics**